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## **SOLAR: A SOFTWARE TOOL FOR METEOROLOGICAL DATA PROCESSING**

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**Abstract:** The current standards for solar components and systems testing (SRB, EN, ISO, DIN, etc.) imply the determination of the system relevant parameters at the monitored locality. In this regard, it is necessary to prepare all the input data for the selected location in order to determine the standard values, such as: thermal collector performance, factor changes in incident angle of radiation, heat capacity, pressure values and various quality tests. The parameters collected with appropriate measuring instruments are necessary for defining the state of atmospheric moisture air (temperature, relative humidity), air movement (speed and wind direction), ambient characteristic at given location (clouds, precipitation, etc.) and parameters that describe the energetic potential of the Sun (total, direct and diffusion radiation). A software tool for meteorological data processing (SOLAR) is designed and constructed so that the collected data of experimental measurements can be effectively and easily processed, with the possibility to present the results in a number of ways. The basic software components are subroutines for data filtering (extracting the minimum, maximum and average values in the selected time interval of observation), data processing (calculation of unknown characteristic values that are based on experimentally measured values), and visualization of results (graphical representation results).

**Keywords:** *software tool, data processing, data filtering, moisture air, solar radiation, energy.*

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## INTRODUCTION

The sudden development and availability of computer technology has enabled fast and efficient manipulation with large databases. There are a number of software that similarly processed data, however, it may be noted that even in similar areas of research there is no strict unification of software input and output variables. An obvious example is a software package called „Climate Consultant“ [1, 2] developed at University of California, Los Angeles, whose primary task is filtering and visualization of meteorological files (extension \*.epw). The data are adjusted to the standardized forms defining the parameters of comfort when people stay indoors as the California Energy Code Comfort Model (2008), ASHRAE Handbook of Fundamentals Comfort Model (2005) and ASHRAE Standard 55-2004 Model. The use of software in which one of the modules deals with similar issues, is widespread in practice. For example, the program „TRNSYS - Transient System Simulation Program“ [3], whose primary function is the simulation of the system work and performance, has a separate module to read and recognize a variety of meteorological data base format (\*.dat, \*.tmy, \*.tmy2, etc.). In a similar way „EnergyPlus program - Energy Simulation Software“ [4], intended to simulate the energy demand of buildings, has a module for processing all the relevant size of a typical meteorological year (\*.iwec), aggregate data about the weather conditions for the given location (\*.stat) and information about the outside design conditions for a given location according to ASHRAE standards (\*.ddy).

While TRNSYS is commercial software written only for Microsoft Windows, Climate Consultant (from the version 3.0) and EnergyPlus are free software compatible with all operating systems. Although TRNSYS and EnergyPlus are both written in FORTRAN, TRNSYS is extendable through any programming language able to compile Windows Dynamic Link Libraries (C, C++, FORTRAN, PASCAL...) and EnergyPlus is extendable only via FORTRAN. Climate Consultant is developed in Java and cannot be extended by user. All described tools are fast, highly graphic and easy to use, understand and maintain. Each has a built in demonstration and automatic install routine.

Based on the analysis of existing similar software solutions, it can be noted that there is no universal format in which the input data is prepared for processing, and that there is no universal way of formatting the results obtained and processed data. Therefore, this approach leaves the possibility to freely accessed creation of algorithms for the creation of databases and their treatment, according to the needs arising from their own research.

## MODEL

Data processing involves modeling the new thermomechanical parameters and variables by using familiar formulas of various complexities whose implementation is significantly simplified by the use of appropriate software routines.

A software tool for meteorological data processing – SOLAR, handles [5] experimental data stored in the database. The format of software database must be such that it contains the INPUT data for  $n=1\div 15$  pre-defined experimental parameters and according to those values calculates  $n=16\div 35$  additional variables as the results (Table 1). The input values  $n=1\div 7$  are placed in database (experimental measurement results),

and values  $n=8\div 15$  are entered by software main window interactive menu. The software calculation procedure is based on Eq.1 to Eq.20.

Table 1. Software database input/output parameters and variables

<i>n</i>	In / Out	Parameter / Variable	Unit	Description	Equation number	
1	Input	Database	$T_{db}$	°C	Dry-bulb temperature	n/a
2			$RH$	%	Relative humidity	
3			$I_H$	Wh/m <sup>2</sup>	Total solar radiation on horizontal surface	
4			$I_{DIF,H}$	Wh/m <sup>2</sup>	Diffuse radiation on horizontal surface	
5			$P_a$	Pa	Atmospheric pressure	
6			$w$	m/s	Wind speed	
7			$WD$	0 ÷ 360°	Wind direction	
8		Interactive menu	$M$	1 ÷ 12	Month of the year	
9			$D$	1 ÷ 31	Day of the month	
10			$N$	1 ÷ 365	Day of the year	
11			$H$	1 ÷ 24	Hour of the day	
12			$\rho_g$	0 ÷ 1	Reflectance of the foreground	
13			$LAT$	degrees	Latitude	
14			$\psi$	0 ÷ 360°	Surface azimuth	
15			$\Sigma$	0 ÷ 90°	Tilt angle	
16	Output	$p_{ws}$	Pa	Water vapor saturation pressure	1	
17		$p_w$	Pa	Water vapor partial pressure	2	
18		$W_s$	kg <sub>w</sub> /kg <sub>da</sub>	Air humidity ratio of saturated air	3	
19		$W$	kg <sub>w</sub> /kg <sub>da</sub>	Air humidity ratio	4	
20		$h$	kJ/kg	Enthalpy of the moist air	5	
21		$T_{wb}$	°C	Wet-bulb temperature	6	
22		$T_d$	°C	Dew-point temperature	7	
23		$\delta$	0 ÷ 90°	Declination	8	
24		$\angle H$	0 ÷ 90°	Hour angle	9	
25		$\beta$	0 ÷ 90°	Solar altitude	10	
26		$\phi$	±90°	Solar azimuth	11	
27		$\gamma$	0 ÷ 90°	Surface-solar azimuth	12	
28		$\Theta$	0 ÷ 90°	Angle of incidence	13	
29		$\Theta_z$	0 ÷ 90°	Zenith angle	14	
30		$R_b$	-	Geometric factor	15	
31		$I_{D,H}$	Wh/m <sup>2</sup>	Direct radiation on horizontal surface	16	
32		$I_{D,T}$	Wh/m <sup>2</sup>	Direct radiation on tilted surface	17	
33		$I_{DIF,T}$	Wh/m <sup>2</sup>	Diffuse radiation on tilted surface	18	
34		$I_{r,T}$	Wh/m <sup>2</sup>	Reflected radiation from the foreground	19	
35		$I_T$	Wh/m <sup>2</sup>	Total solar radiation on tilted surface	20	

When determining a number of moist air properties (the saturation humidity ratio primarily), the water vapor saturation pressure  $p_{ws}$  is required. The Eq.1 is created by fitting the curve (with coefficient of determination value  $r^2=0.9999076$ ) to data presented in Table 2, where equation constants are  $C_1=-0.51429817$ ,  $C_2=1.076863162$  and  $C_3=-20.1577755$ .

$$p_{ws} = C_1 + C_2 \cdot e^{\left(\frac{-T_{db}}{C_3}\right)} \quad (1)$$

Table 2. The water vapor saturation pressure dependence of dry-bulb temperature [6, 7]

$T_{db}$	$^{\circ}C$	0	10	20	30	40	50	60	70
$p_{ws}$	<i>kPa</i>	0.61	1.23	2.34	4.24	7.37	12.33	19.92	31.17

The water vapor partial pressure  $p_w$  is the product of the relative humidity  $RH$  and the water vapor saturation pressure (Eq.2) [8].

$$p_w = (RH/100) \cdot p_{ws} \quad (2)$$

Saturation humidity ratio  $W_s$  is the humidity ratio of moist air saturated with respect to water (or ice) at the same temperature and pressure (Eq.3). Humidity ratio  $W$  of a given moist air sample is defined as the ratio of the mass of water vapor to the mass of dry air contained in the sample (Eq.4).

$$W_s = (M_w/M_a) \cdot [p_{ws}/(p_a - p_{ws})] \quad (3)$$

$$W = (M_w/M_a) \cdot [p_w/(p_a - p_w)] \quad (4)$$

where equation constants are  $M_w=18.016 \text{ kg/kmol}$ ,  $M_a=28.964 \text{ kg/kmol}$  and  $P_a=101325 \text{ Pa}$ .

The enthalpy of a mixture of perfect gases equals the sum of the individual partial enthalpies of the components. Therefore, the enthalpy of moist air can be written by Eq.5.

$$h = c_{p,a} \cdot T_{db} + W \cdot (r_o + c_{p,w} \cdot T_{db}) \quad (5)$$

where equation constants are  $c_{p,a}=1.004 \text{ kJ/kgK}$ ,  $r_o=2500 \text{ kJ/kg}$  and  $c_{p,w}=1.805 \text{ kJ/kgK}$ .

The value of wet-bulb temperature  $T_{wb}$ , which satisfies Eq.(6) for given values of  $T_{wb}$ ,  $W$  and  $W_s$  is calculated by using the assumption-iteration method.

$$W = \frac{(2500 - 2.381 \cdot T_{wb}) \cdot W_s - (T_{db} - T_{wb})}{2500 - 1.805 \cdot T_{db} - 4.186 T_{wb}} \quad (6)$$

Dew-point temperature  $t_d$  is the temperature of moist air saturated at the same pressure  $p$ , with the same humidity ratio  $W$  as that of the given sample of moist air. It is defined as the solution  $t_d = t_d(p, W)$  of the Eq.7 [8].

$$W_s(p, t_d) = W \tag{7}$$

To find the solar altitude  $\beta$  and the azimuth  $\phi$  when the hour angle  $\angle H$ , the latitude  $LAT$ , and the declination  $\delta$  are known, the following Eq.8 to Eq.11 may be used.

$$\delta = 23.45 \cdot \sin[360^\circ(284 + N)/365] \tag{8}$$

$$\angle H = 15 \cdot H - 180^\circ \tag{9}$$

$$\sin \beta = \cos(LAT) \cdot \cos \delta \cdot \cos(\angle H) + \sin(LAT) \cdot \sin \delta \tag{10}$$

$$\cos \phi = \frac{\sin \beta \cdot \sin(LAT) - \sin \delta}{\cos \beta \cdot \cos(LAT)} \tag{11}$$

The surface-solar azimuth  $\gamma$  is the angular difference, described in Eq.12, between the solar azimuth  $\phi$  and the surface azimuth  $\psi$ .

$$\gamma = \phi - \psi \tag{12}$$

For a surface with a tilt angle  $\Sigma$  (measured from the horizontal), the angle of incidence  $\theta$  between the direct solar beam and the normal to the surface is given by Eq.13. All previously used solar angles with respect to a tilted surface are described on Fig.1.

$$\cos \Theta = \cos \beta \cdot \cos \gamma \cdot \sin \Sigma + \sin \beta \cdot \cos \Sigma \tag{13}$$

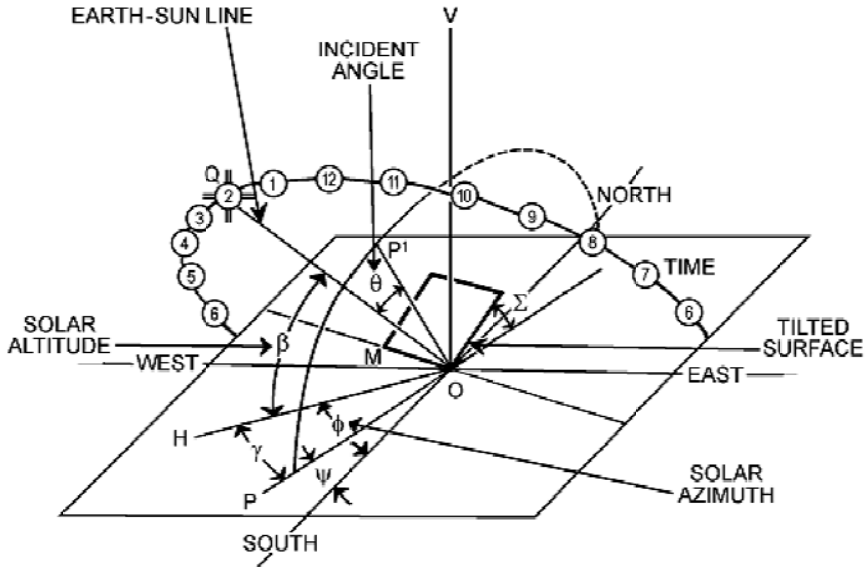


Figure 1. Solar Angles with Respect to a Tilted Surface [9]

Zenith angle  $\theta_Z$  defined with Eq.14 and geometric factor  $R_b$  calculated from Eq.15 are used for calculating the value of the intensity of the direct normal radiation  $I_{D,T}$ , at the terrestrial surface of any orientation and tilt with an incident angle  $\theta$  on a clear day.

$$\Theta_Z = 90 - \beta \quad (14)$$

$$R_b = \cos\Theta / \cos\Theta_Z \quad (15)$$

The intensity of the direct normal radiation  $I_{D,H}$ , at the terrestrial horizontal surface, can be calculated from the Eq.16.

$$I_{D,H} = I_H - I_{DIF,H} \quad (16)$$

The intensity of the direct normal radiation  $I_{D,T}$ , at the terrestrial surface of any orientation and tilt with an incident angle  $\theta$  on a clear day, can be calculated from the Eq.17.

$$I_{D,T} = I_{D,H} \cdot R_b \quad (17)$$

The intensity of the diffuse radiation  $I_{DIF,T}$ , at the terrestrial surface of any orientation and tilt with an incident angle  $\theta$  on a clear day, can be calculated from the Eq.18.

$$I_{DIF,T} = I_{DIF,H} \cdot [(1 + \cos\Sigma) / 2] \quad (18)$$

The reflected radiation  $I_r$  from the foreground, when the reflectance  $\rho_g$  is known, is given by the Eq.19.

$$I_R = I_H \cdot \rho_g \cdot [(1 - \cos\Sigma) / 2] \quad (19)$$

The intensity of the total solar radiation  $I_T$ , at the terrestrial surface of any orientation and tilt with an incident angle  $\theta$  on a clear day, can be calculated from the Eq.20. [18]

$$I_T = I_{D,T} + I_{DIF,T} + I_{R,T} \quad (20)$$

## SOFTWARE CHARACTERISTICS

SOLAR is portable, flexible, secure, scalable and easy-to-use software freely available as a web application requiring no download or installation. Software architecture followed by brief description of software implementation and usage is given below.

## Software architecture

Software architecture involves the components of a software system and the relationships between those elements [10]. In the case of web-based software modules, databases and web servers are the components of system and mechanisms of information exchange between system components are described with relationships among them [11]. In order to create and maintain the software architecture, structure of a system has to be specified and standard design practices have to be followed.

A multi-tier architecture is architectural pattern used to divide functionality of a system into a number of layers [12]. This architecture is widely used for development of different web-based applications because it enhances reusability, scalability and flexibility of application [13].

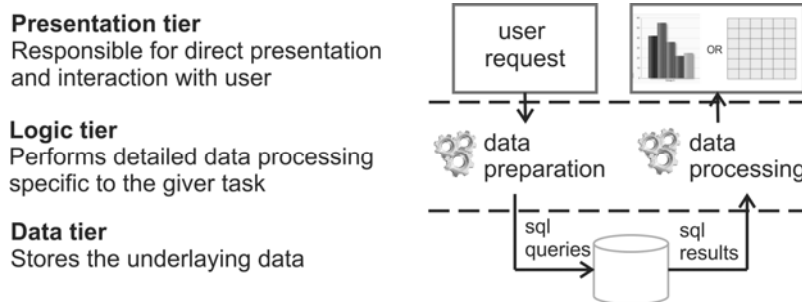


Figure 2. SOLAR architecture

For example, module for parsing and processing CSV (Comma Separated Values) files created for one application can be reused in other applications. SOLAR web-based software has three tiers with architecture detailed in Fig. 2.

## Software implementation

SOLAR is built on open source and platform independent solutions, with Apache HTTP Server 2.2 and MySQL 5.6 at the back end and PHP 5.3 [14, 15], HTML [16], CSS [17] and JavaScript at the front end. This software is available online through any Web browser at <http://solar.mas.bg.ac.rs/software.html>.

With interactive and user-friendly graphical interface, SOLAR is easy to use for all users. Also, user guide is available as a PDF, downloadable from manual section<sup>1</sup>. Software can work with default database entries but user can provide its own file with appropriate data in suitable format (template is available for download from manual section) to fill the database. Software-provided data are available for any user while user-provided data are available only for the user who provides it. After the user chooses a type of filtering (minimum, maximum and average), time interval (hourly, daily and monthly or arbitrarily specified interval in specific format), parameters (given in Table 1) and result representation (graphical, tabular), the software prepares data for further use based on selected constraints.

<sup>1</sup> <http://solar.mas.bg.ac.rs/manual.html>

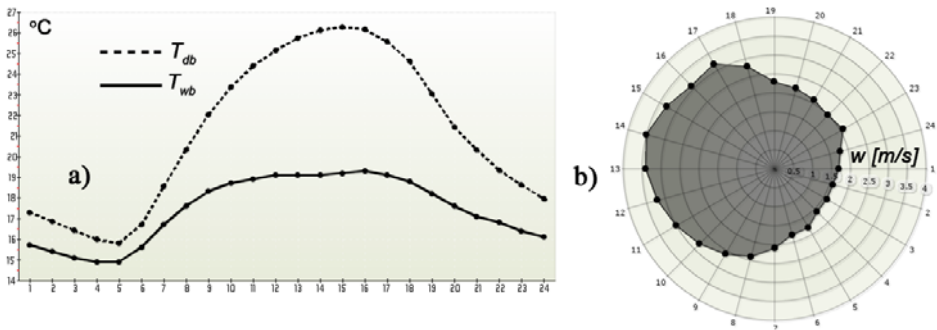


Figure 3. Air properties graphs: a) Dry-bulb and wet-bulb temperatures; b) Wind speed

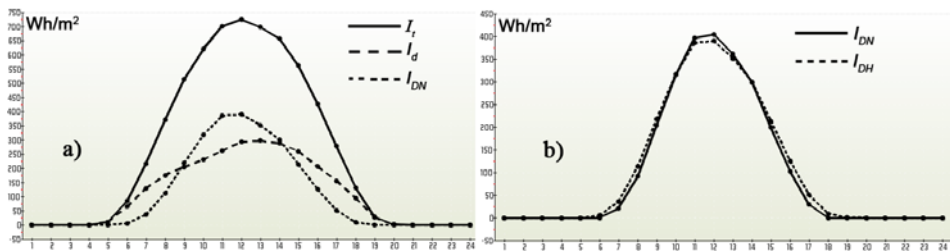


Figure 4. Surface radiation graphs: a) Total solar, Diffuse and Direct radiation; b) Direct radiation on surface of any orientation and tilt angle and Direct radiation on horizontal surface

Then, corresponding values are read from the database and new ones are calculated according to formulas given in previous section. All values are standardized, normalized and grouped depending on selected result representation. Finally, obtained results are submitted to user in one of two formats – tabular format and graphical format. Results are available for download as PNG file for graphical representation and as CSV file for tabular representation.

The examples of graphical representation of the results are presented in Fig. 3 and Fig. 4. Fig. 3 illustrates the simple visualization of hourly averaged input database data, during the selected period 1<sup>st</sup> June – 30<sup>th</sup> August. Software is reading the input values of dry-bulb and wet-bulb temperatures (Fig. 3a) and wind speed (Fig. 3b) from the database, calculates average values and draws the graphs. The input data and calculated variables could be combined on the same graph. For example, it is possible to present total solar radiation (from database), diffuse radiation (from database) and direct radiation (calculated variable) in a same graph (Fig. 4a). However, if there is a need to explore database in more details, there is a software possibility for selecting additional criteria from interactive menu. For example, the direct radiation on surface (South orientation) with tilt angle (45 degrees) and with included reflectance of foreground (0.10) could be presented along with direct radiation on horizontal surface in a same graph (Fig. 4b), despite the fact that all values are calculated.

The practical application of SOLAR is possible within solving and calculation of various ranges of different problems. For example, this type of data processing could bring great benefit in the analysis and simulation of greenhouses performances [19],



energy consumption for different greenhouse constructions [20, 21], exploring possibilities for renewable energy storage [22], or dealing with different solar energy related problems and applications [23, 24], etc.

## CONCLUSIONS

Based on current scientific knowledge in the field of applied thermodynamics, a software application for processing data collected by experimental measurements was developed. The software contains modules for data filtering, data processing and data visualization. The software significantly shortens the time needed for problem analysis, trend monitoring changes in relevant process parameters or extract characteristic values of the observed desired intervals. Developed software is easy to use and supported by accompanying documentation, maintenance and training, with the possibility of module extension according to the user demands. The implementation of such a computer program that automates the calculation and provides a graphical picture of the changes observed parameters can enable rapid implementation of numerous analyses which are based on multi-criteria basis. The possibility of exporting the fitted values in the new - an updated database, gives this application a special importance, especially for displaying the data obtained in the so-called "user friendly" format, that is accepted by the huge number of applications that are used in mathematical and statistical analysis of data.

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## SOLAR: SOFTVER ZA FILTRIRANJE, OBRADU I VIZUELIZACIJU PRIKUPLJENIH METEOROLOŠKIH PODATAKA

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**Sažetak:** Aktuelni standardi za ispitivanje solarnih komponenata i sistema (SRB, EN, ISO, DIN i drugi) podrazumevaju određivanje svih relevantnih parametara rada instalacije na posmatranom lokalitetu. S tim u vezi, neophodno je pripremiti sve ulazne podatke za odabranu lokaciju radi određivanja standardom definisanih veličina, kao što su: toplotni učinak kolektor, faktor promene upadnog ugla zračenja, toplotnog kapaciteta, padova pritisaka i raznih testova kvaliteta. Veličine koje su od značaja za proračun se mere odgovarajućim mernim instrumentima i neophodne su za definisanje stanja vlažnog atmosferskog vazduha (temperatura, relativna vlažnost), kretanja vazduha (brzina i pravac strujanja vetra), ambijentalnih karakteristika atmosfere na posmatranoj lokaciji (oblačnost, količina padavina, i slično) kao i veličina koje oslikavaju energetske potencijale Sunca na posmatranoj lokaciji (ukupno, direktno i difuzno zračenje). Softver za filtriranje, obradu i vizuelizaciju prikupljenih meteoroloških podataka - SOLAR, osmišljen je i izrađen tako da prikupljene podatke eksperimentalnih merenja efikasno i jednostavno procesira, a dobijene rezultate potom predstavi korisniku. Osnovne komponente softvera su subrutine za filtriranje podataka (izdvajanje minimalnih, maksimalnih i prosečnih vrednosti u željenom vremenskom intervalu posmatranja), za obradu podataka (izračunavanje nepoznatih karakterističnih veličina koje su od značaja za posmatrani proces na osnovu eksperimentalno merenih veličina) i vizuelizaciju rezultata (grafičko predstavljanje rezultata sa mogućnošću uporednog prikazivanja srodnih veličina i mogućnošću eksportovanja u druge formate pogodne za dalju analizu).

**Ključne reči:** softver, obrada podataka, filtriranje podataka, vlažan vazduh, Sunčevo zračenje, energija.

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